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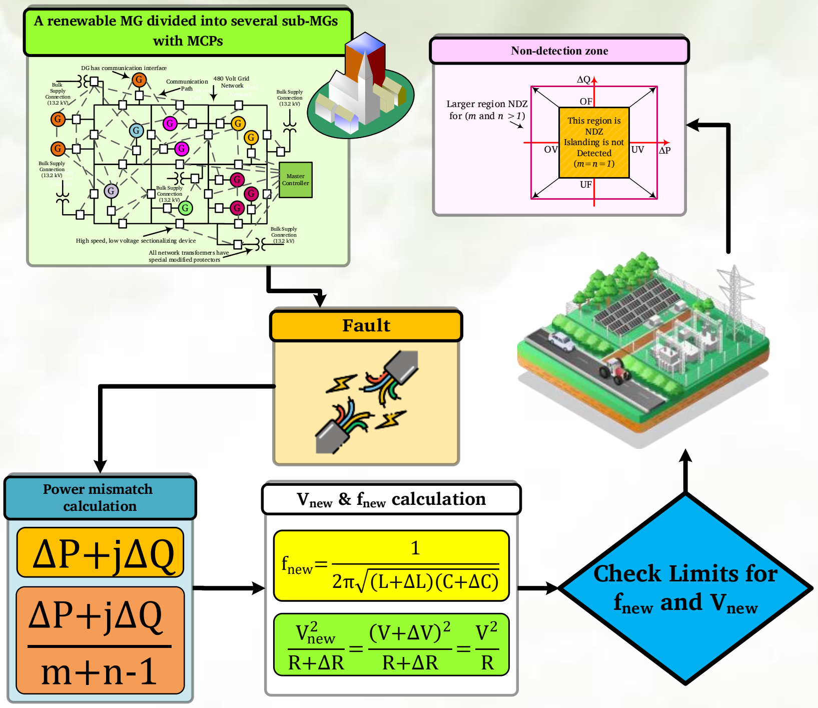
Highlights

- Presenting the power equations for active and reactive power in renewable-energy-based multi-microgrids
- Presenting procedures for over/under voltage protection, over/under frequency protection
- The proposed approach is very broad across different types of microgrids
- The proposed local islanding identification methods often have a significant NDZ

Graphical Abstract



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Power Equations for Non-Detection Zone of Islanding Detection in Renewable-Energy-based Microgrids with Multiple Connection Points to Micro-Grids

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ABSTRACT

Microgrids (MGs), which can incorporate renewable energies such as wind and solar, can be divided into several sub-MGs with multiple connection points (MCPs) to the grids. However, this configuration is not ideal for MG operation due to the lack of adequate protection and operation mechanisms that ensure the safe and reliable functioning of distributed generation. A key issue with these MGs is the identification of islanding, which is challenging due to the presence of a broad non-detection zone (NDZ). Passive islanding identification approaches primarily depend on over/under voltage protection (OVP/UVP), over/under frequency protection (OFP/UFP), and monitoring metrics, such as phase jump at the point of common coupling (PCC). This study examines the power equations for real and reactive power in renewable-energy-based MGs (referred to as renewable MGs) with multiple connections to different grids and MGs, which are of significant size. The analysis focuses on the NDZ of OVP/UVP and OFP/UFP approaches. Passive approaches observe the changing system parameters that occur when the MG is isolated, while active methods depend on the system's reaction to a minor disturbance introduced to identify the isolation situation. Traditional passive islanding detection approaches exhibit a significant NDZ that may compromise the accuracy of islanding detection in these types of MGs. Even if one grid is disconnected, the MG remains connected to other grids, preventing islanding. Consequently, typical active islanding detection methods are unable to identify the off-grid status.

1. Introduction

Islanding identification is crucial in the process of connecting microgrids (MGs) to electrical grids. The detection approaches are primarily categorized into remote and local methods, which depend on electrical signal measurements taken at the grid and MG sides, respectively. MGs are capable of harnessing renewable energies for power generation.

They can be divided into smaller sub-MGs with MCPs to the rest of the grids. However, the current network protection systems and operations do not support the immune and dependable operation of distributed generation, making them unsuitable for MG operation [1-3]. The majority of remote techniques used for islanding identification depend on the connectivity between the power grid and the MG. Remote methods lack a non-detection zone (NDZ) and are, hence, significantly reliable techniques for detecting islanding. Although the implementation of remote methods can be costly for small MGs, they offer significant advantages for large MG practices [4-6]. Local islanding identification is conducted by passive, active, and hybrid techniques by finding grid parameters at the MG side, including voltage, frequency, current, and harmonic distortion. Passive approaches observe the changing system characteristics when the microgrid is isolated. On the other hand, active methods depend on the grid's reaction to a minor injected disturbance to detect the islanding condition. The hybrid strategy is a fusion of the active and passive techniques used to overcome NDZ [7-19]. Islanding in a power network can only occur when there is an equilibrium between the active and reactive powers. The equations for P and Q, as well as the NDZ of the MG for grid connection, are developed and investigated in the references [20, 21]. The utilization of power equations for NDZ in islanding detection of MG with several connection points to grids and/or other MGs is thoroughly studied in reference [22]. This study investigates the power equations for real and reactive power in the presence of NDZ using OVP/UVP (overvoltage/undervoltage protection) and OFP/UFP (over-frequency/under-frequency protection) approaches. The analysis focuses on significant-size renewable MGs that are connected to several grids and other MGs. Traditional passive islanding identification approaches have a significant non-detection zone (NDZ), potentially compromising the accuracy of islanding identification in these specific kinds of MGs. Even if one grid is disconnected, the MG remains connected to other grids, preventing islanding. Consequently, typical active islanding identification methods are unable to identify the off-grid status. The paper presents active, reactive power equations and procedures for OVP/UVP and OFP/UFP and analyzes the NDZ area for MGs. The results show the broad NDZ area for OUP and OVP methods in different types of MGs.

The rest of the paper is organized as follows: Section 2 explains the MGs, MCPs, and islanding techniques. Section 3 describes and analyzes passive method equations of islanding. Then, the paper is focused on relation criteria and thresholds of frequency, active power, and reactive power. Concluding remarks are finally presented in Section 4.

2. Microgrids with MCPs to Grids and/or Microgrids

Nowadays, renewable MGs are developed and use different kinds of energy, such as solar energy, to produce power. Some power consumers, such as hospitals and airports, are some examples of MGs with MCPs to grids constituting several large and important sub-MGs that should always be in service. Therefore, the stability of such unified MGs is so important while all low-voltage cells are connected and synchronized. One example of large MGs with two connection points to other grids is illustrated in Figure 1, but islanding identification in this kind of MGs is more complicated compared to other MGs, as mentioned in [1-3]. The primary limitation of passive and active techniques lies in their reliance on the fluctuations of measured quantities, which may not be substantial, especially in scenarios such as i) microgrids with NCPs to the grid, ii) microgrids connected to multiple grids, and iii) microgrids with numerous smaller sub-microgrids. Figure 2 depicts a highly sophisticated low-voltage grid network capable of functioning as a unified MG, where all low-voltage cells are interconnected and synchronized. Alternatively, the network is divided into separate autonomous cells. Using local passive and active islanding identifications is not recommended here since these kinds of MGs have a large NDZ.

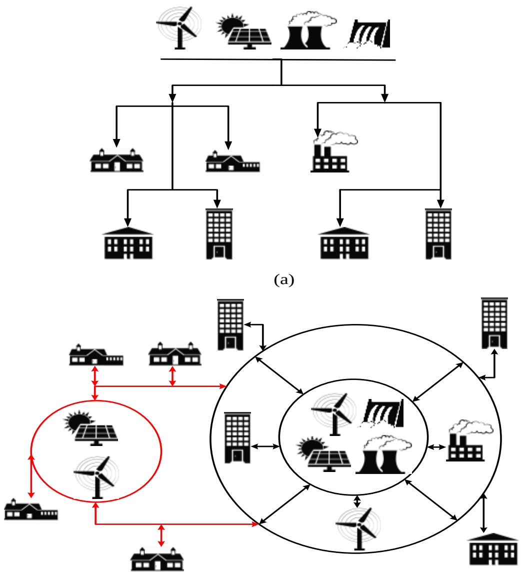
(a)
(b)

Figure 1. Topologies for grids; (a) Traditional grid, (b) large renewable MG with two connection points to grids.

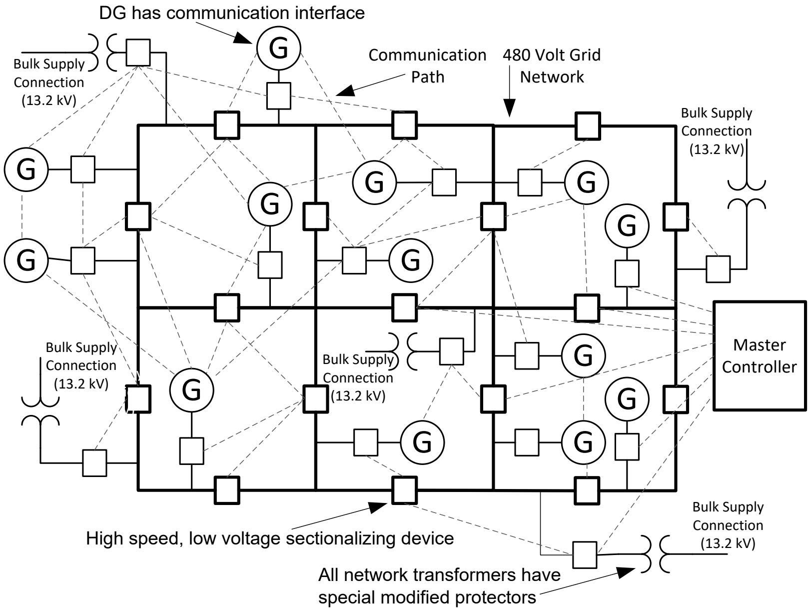

Figure 2. A renewable MG divided into several sub-MGs with MCPs to the rest of the grids; similar to figures 2-11 given in [1].

3. Power Equations for Non-Detection Zone in Renewable Microgrids with MCPs to Grids and/or Microgrids

Figure 3 illustrates a universal method for examining islanding in a renewable MG with MCPs connected to distinct grids and other MGs. A regional RLC load is placed at the point of common coupling (PCC). The resonant frequency f and power quality Qf is defined as follows [20, 21]:

$$f = \frac{1}{2\pi\sqrt{LC}} \tag{1}$$

$$Q_f = R\sqrt{\frac{C}{L}} \tag{2}$$

$$Q_L = \frac{V^2}{2\pi f L} \tag{3}$$

$$Q_C = 2\pi f C V^2 \tag{4}$$

where f(Hz), L(H), C(F), R(Ω), V(v), Q_L(kVAR) and Q_C(kVAR) are frequency, reactance, capacitance, resistance, voltage, reactive power of reactance, and reactive power of capacitance, respectively. In Figure 3, the power mismatch $\Delta P + j\Delta Q$ is observed between MG generation and RLC load. Prior to removing Grid 1, the power is supported by grids and the rest of the MGs. For simplicity, suppose every MGs and grids equally supply this power mismatch. So, every MG and grid supply power mismatch is $\frac{\Delta P+j\Delta Q}{m+n-1}$, where m and n denote the number of MGs and grids, respectively. In Figure 4, Grid 1 is disconnected from the network, and the power mismatch $\frac{\Delta P+j\Delta Q}{m+n-1}$ can be represented as mismatch loads $\Delta R.\Delta L.\Delta C$. The frequency and voltage values are modified to V_{new} and f_{new}, correspondingly. Nevertheless, the limited magnitude of these changes can be attributed to the interconnection between MG and the other power systems.

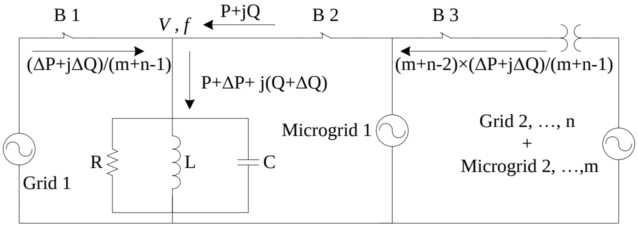

Figure 3. A renewable MG with MCPs to grids for islanding study.

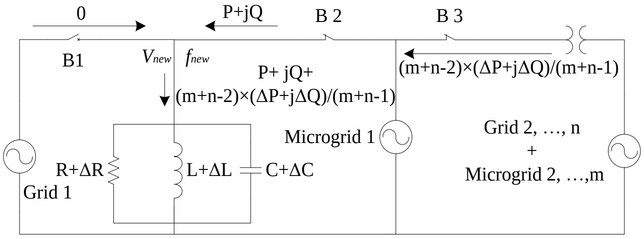

Figure 4. Circuit breaker 1 (B1) opens and mismatch power $\frac{\Delta P+j\Delta Q}{m+n-1}$ represented by $\Delta R.\Delta L.\Delta C$.

$$f_{new} = \frac{1}{2\pi\sqrt{(L+\Delta L)(C+\Delta C)}} \tag{5}$$

$$\begin{aligned}\frac{f_{new}-f}{f} &= \frac{\frac{1}{2\pi\sqrt{(L+\Delta L)(C+\Delta C)}} - \frac{1}{2\pi\sqrt{LC}}}{\frac{1}{2\pi\sqrt{LC}}} \\ &= \frac{\frac{1}{2\pi\sqrt{(L+\Delta L)(C+\Delta C)}}}{\frac{1}{2\pi\sqrt{LC}}} - \frac{\frac{1}{2\pi\sqrt{LC}}}{\frac{1}{2\pi\sqrt{LC}}} \\ &= \frac{\sqrt{LC}}{\sqrt{(L+\Delta L)(C+\Delta C)}} - 1\end{aligned} \tag{6}$$

In order to use f_{max} and f_{min} as thresholds for under/over frequency (UF/OF), the following criteria need to be satisfied:

$$\begin{gathered}\frac{f_{min}-f}{f} \leq \frac{\sqrt{LC}}{\sqrt{(L+\Delta L)(C+\Delta C)}} - 1 \leq \frac{f_{max}-f}{f} \\ \frac{f_{min}}{f} - 1 \leq \frac{\sqrt{LC}}{\sqrt{(L+\Delta L)(C+\Delta C)}} - 1 \leq \frac{f_{max}}{f} - 1 \\ \frac{f_{min}}{f} \leq \frac{\sqrt{LC}}{\sqrt{(L+\Delta L)(C+\Delta C)}} \leq \frac{f_{max}}{f} \\ \left(\frac{f_{min}}{f}\right)^2 \leq \frac{LC}{(L+\Delta L)(C+\Delta C)} \leq \left(\frac{f_{max}}{f}\right)^2 \\ \left(\frac{f_{min}}{f}\right)^2 \leq \frac{LC}{LC+L\Delta C+C\Delta L+\Delta L\Delta C} \leq \left(\frac{f_{max}}{f}\right)^2\end{gathered} \tag{7}$$

where f_{max} and f_{min} are maximum and minimum frequency, respectively. Simplifying with the approximation of $\Delta L\Delta C \approx 0$:

$$\begin{gathered}\left(\frac{f_{min}}{f}\right)^2 \leq \frac{LC}{LC+L\Delta C+C\Delta L} \leq \left(\frac{f_{max}}{f}\right)^2 \\ \left(\frac{f}{f_{max}}\right)^2 \leq \frac{LC+L\Delta C+C\Delta L}{LC} \leq \left(\frac{f}{f_{min}}\right)^2 \\ \left(\frac{f}{f_{max}}\right)^2 \leq 1+\frac{\Delta C}{C}+\frac{\Delta L}{L} \leq \left(\frac{f}{f_{min}}\right)^2 \\ \left(\frac{f}{f_{max}}\right)^2 - 1 \leq \frac{\Delta C}{C}+\frac{\Delta L}{L} \leq \left(\frac{f}{f_{min}}\right)^2 - 1\end{gathered} \tag{8}$$

$\frac{\Delta Q}{m+n-1}$ mismatch can be shown as:

$$\begin{aligned}\frac{\Delta Q}{m+n-1} &= V^2\left(\frac{1}{2\pi f(L+\Delta L)} - 2\pi f(C+\Delta C)\right)\\ &= V^2\left[\frac{1}{2\pi f L\left(1+\frac{\Delta L}{L}\right)} - 2\pi f C\left(1+\frac{\Delta C}{C}\right)\right]\\ &= \left[\left(\frac{V^2}{2\pi f L}\right)\frac{1}{\left(1+\frac{\Delta L}{L}\right)} - (2\pi f C V^2)\left(1+\frac{\Delta C}{C}\right)\right]\\ &= \frac{Q_L}{\left(1+\frac{\Delta L}{L}\right)} - Q_C\left(1+\frac{\Delta C}{C}\right)\end{aligned} \tag{9}$$

Based on Q_f definition:

$$Q_f \times P = Q_L = Q_C \tag{10}$$

Normalize $\frac{\Delta Q}{m+n-1}$ in Equation (9) based on P:

$$\begin{aligned}\frac{\Delta Q}{(m+n-1)P} &= \frac{\left(\frac{Q_L}{P}\right)}{\left(1+\frac{\Delta L}{L}\right)} - \left(\frac{Q_C}{P}\right)\left(1+\frac{\Delta C}{C}\right)\\ &= \frac{Q_f}{\left(1+\frac{\Delta L}{L}\right)} - Q_f\left(1+\frac{\Delta C}{C}\right)\\ &= Q_f\left[\frac{1}{\left(1+\frac{\Delta L}{L}\right)} - \left(1+\frac{\Delta C}{C}\right)\right]\\ &= Q_f\,\frac{1-\left(1+\frac{\Delta L}{L}\right)\left(1+\frac{\Delta C}{C}\right)}{1+\frac{\Delta L}{L}}\\ &= Q_f\,\frac{1-\left(1+\frac{\Delta C}{C}+\frac{\Delta L}{L}+\frac{\Delta L}{L}\times\frac{\Delta C}{C}\right)}{1+\frac{\Delta L}{L}}\\ &= Q_f\,\frac{-\left(\frac{\Delta C}{C}+\frac{\Delta L}{L}+\frac{\Delta L}{L}\times\frac{\Delta C}{C}\right)}{1+\frac{\Delta L}{L}}\end{aligned} \tag{11}$$

Simplified with approximation of $\Delta L \Delta C \approx 0$ and $1+\frac{\Delta L}{L} \approx 1$:

$$\frac{\Delta Q}{(m+n-1)P} \approx -Q_f\left(\frac{\Delta C}{C}+\frac{\Delta L}{L}\right) \tag{12}$$

From Equation (8) and Equation (12), NDZ of reactive power is:

$$\begin{aligned}&\left(\frac{f}{f_{max}}\right)^2 - 1 \le \frac{\Delta Q}{-Q_f(m+n-1)P} \le \left(\frac{f}{f_{min}}\right)^2 - 1\\ &Q_f\left(\left(\frac{f}{f_{max}}\right)^2 - 1\right) \le \frac{-\Delta Q}{(m+n-1)P} \le Q_f\left(\left(\frac{f}{f_{min}}\right)^2 - 1\right)\end{aligned} \tag{13}$$

Finally,

$$Q_f\left(1-\left(\frac{f}{f_{min}}\right)^2\right) \leq \frac{\Delta Q}{(m+n-1)P} \leq Q_f\left(1-\left(\frac{f}{f_{max}}\right)^2\right) \tag{14}$$

By the same token, the correlation between the voltage and active power is deduced. Prior to the disconnection of Grid 1, the MG active power is V^2/R. After disconnecting Grid 1, the load active power is $V^2/(R+\Delta R)$. If it is assumed that the system is under constant power regulation, then the equilibrium of active power may be expressed as:

$$\frac{V_{new}^2}{R+\Delta R} = \frac{(V+\Delta V)^2}{R+\Delta R} = \frac{V^2}{R} \tag{15}$$

Equation (15) can be simplified as:

$$\begin{aligned} &\frac{(V+\Delta V)^2}{V^2} = \frac{R+\Delta R}{R} \\ &\frac{V^2+2V\Delta V+\Delta V^2}{V^2} = 1+\frac{\Delta R}{R} \\ &1+\frac{2\Delta V}{V}+\frac{\Delta V^2}{V^2} = 1+\frac{\Delta R}{R} \\ &2\frac{\Delta V}{V}+\left(\frac{\Delta V}{V}\right)^2 = \frac{\Delta R}{R} \end{aligned} \tag{16}$$

Before disconnecting Grid 1 from the system, Grid 1 supplies $\frac{\Delta P}{m+n-1}$ to the RLC load:

$$\frac{\Delta P}{m+n-1} = \frac{V^2}{R+\Delta R} - \frac{V^2}{R} \tag{17}$$

Normalize $\frac{\Delta P}{m+n-1}$ with $P = \frac{V^2}{R}$:

$$\begin{aligned} \frac{\Delta P}{(m+n-1)P} &= \frac{\frac{V^2}{R+\Delta R}-\frac{V^2}{R}}{\frac{V^2}{R}} = \frac{\frac{RV^2-(R+\Delta R)V^2}{(R+\Delta R)R}}{\frac{V^2}{R}} \\ &= \frac{R-(R+\Delta R)}{R+\Delta R} = -\frac{\Delta R}{R+\Delta R} = -\frac{\frac{\Delta R}{R}}{\frac{R+\Delta R}{R}} = -\frac{\frac{\Delta R}{R}}{1+\frac{\Delta R}{R}} \end{aligned} \tag{18}$$

Substituting Equation (16) into Equation (18) and simplifying the equation with $V_{new} = \Delta V + V$, it is obtained:

$$
\begin{aligned}
\frac{\Delta P}{(m+n-1)P} &= -\frac{\frac{\Delta R}{R}}{1+\frac{\Delta R}{R}} = -\frac{2\frac{\Delta V}{V}+\left(\frac{\Delta V}{V}\right)^2}{1+2\frac{\Delta V}{V}+\left(\frac{\Delta V}{V}\right)^2} \\
&= -\frac{1+2\frac{\Delta V}{V}+\left(\frac{\Delta V}{V}\right)^2-1}{1+2\frac{\Delta V}{V}+\left(\frac{\Delta V}{V}\right)^2} = -\frac{\left(\frac{\Delta V}{V}+1\right)^2-1}{\left(\frac{\Delta V}{V}+1\right)^2} \\
&= \frac{1-\left(\frac{\Delta V}{V}+1\right)^2}{\left(\frac{\Delta V}{V}+1\right)^2} = \frac{1}{\left(\frac{\Delta V+V}{V}\right)^2}-1 \\
&= \frac{V^2}{(\Delta V+V)^2}-1 = \frac{V^2}{V_{new}^2}-1 = \left(\frac{V}{V_{new}}\right)^2-1
\end{aligned}
\tag{19}
$$

To ensure that V_{new} falls between the voltage thresholds, V_{min} and V_{max}, the following condition must be satisfied, resulting in the non-disruptive zone (NDZ) of active power:

$$
\left(\frac{V}{V_{max}}\right)^2 - 1 \leq \frac{\Delta P}{(m+n-1)P} \leq \left(\frac{V}{V_{min}}\right)^2 - 1 \tag{20}
$$

where V_{min}, V_{max} are minimum and maximum voltage, respectively. Therefore, the NDZ for UV/OV and UF/OF approaches to one MG and one grid $m = 1$ and $n = 1$ can be observed in Figure 5. Mathematically approach, in Equations (14) and (20), power mismatch $\frac{\Delta P}{m+n-1}$ and $\frac{\Delta Q}{m+n-1}$ are smaller than ΔP *and* ΔQ when m *and* n are larger than 1, and the power mismatch of the MG is lesser. Therefore, the region of the NDZ increases. For example, based on standard IEEE 1547 [15] in Equations (14) and (20) for $Q_f = 1.\ f_{min} = 0.99f.\ f_{max} = 1.01f.V_{min} = 0.9V.V_{max} = 1.1V$:

$$
(-2.03\%) \times (m+n-1) \leq \frac{\Delta Q}{P} \leq (1.97\%) \times (m+n-1) \tag{21}
$$

$$
(-17.36\%) \times (m+n-1) \leq \frac{\Delta P}{P} \leq (23.46\%) \times (m+n-1) \tag{22}
$$

Considering Equations (21) and (22), The region of NDZ in passive islanding identification approaches, as shown in Figure 5, expands due to the compensation of ΔP and ΔQ by other grids and MGs. Consequently, no discrepancies appear in the frequency and voltage. As a result, the passive islanding identification approaches will exhibit significant NDZs for these particular kinds of MGs. Furthermore, the connection of many grids to the MG ensures that even if one grid is disconnected, islanding can be prevented. Consequently, typical active islanding identification approaches will be unable to identify the off-grid status.

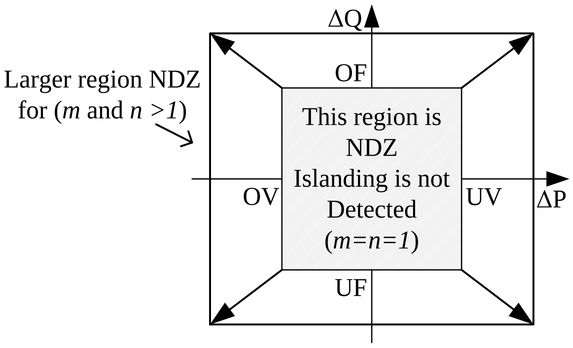

Figure 5. The NDZ of OV/UV and OF/UF for MG in Figure 3. $m = n = 1$, m and $n > 1$.

4. Conclusions

MGs that are presented constitute some sub-MGs with MCPs to different grids. As a consequence of a large NDZ area in these kinds of MGs, traditional methods cannot always detect islanding. OVP/UVP and OFP/UFP are primarily employed as passive islanding detection techniques, monitoring parameters such as voltage amplitude and frequency at the PCC. This study presents a derivation and analysis of the equations for real and reactive power, as well as the procedures for OVP/UVP and OFP/UFP. The presented equations can be applied to any type of multi-terminal microgrid. The findings indicate that the NDZ of the OVP and UVP methods is very broad across different types of MGs. Identifying islanding in renewable microgrids can be complex due to their ability to remain stable by connecting to many grids. Additionally, local islanding identification methods often have a significant NDZ. Even if one grid is disconnected, the renewable microgrid remains connected to other grids, preventing islanding. Consequently, conventional active islanding identification methods are unable to detect the off-grid condition.

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. The ethical issues, including plagiarism, informed consent, misconduct, data fabrication and/or falsification, double publication and/or submission, redundancy, have been completely observed by the authors.

Credit Authorship Contribution Statement

Saman Darvish Kermani: Conceptualization, Formal analysis, Investigation, Methodology, Resources, Roles/Writing- original draft. **Vahid Davatgaran:** Methodology, Resources, Roles/Writing - original draft, Writing - review & editing. **Arsalan Beigzadeh**: Conceptualization, Supervision, Methodology, Roles/Writing- original draft. **Mahmood Joorabian:** Conceptualization, Project administration, Validation, Visualization, Roles/Writing - original draft.

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